MODIS CALIBRATION PLAN REVIEW

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Held at the Goddard Space Flight Center
April 13 - 14, 1994

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CHAPTER STRUCTURE

The Calibration Plan addresses **how** the calibration and characterization inputs for MODIS will be obtained. For this reason, and where appropriate, the presentations in this review and the chapters in the Calibration Plan have been ~~have been~~ structured as follows:

1. Objective
2. Methodology
3. Error budget
4. Verification
5. Personnel
6. Schedule
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Note: When completed, the ATBD (Appendix A) will describe **what** will be done with the calibration inputs to determine calibration coefficients and geolocation data as a function of time.

CALIBRATION PHILOSOPHY

General

Many independent, precise methods used. This enables systematic errors to be pinpointed and corrected, providing the possibility for highly accurate absolute calibrations of the 36 spectral bands. Some methods are for short time scales (within orbit), others for one to ≥15 years.

Preflight

Performance characterization emphasized.

Calibration conducted against sun as well as artificial secondary-standard sources. The latter are cross-calibrated against primary standard sources from national standards laboratories, and other EOS calibration sources using ultra-stable radiometers.

Preflight calibration transferred to orbit by on-board calibrators. Detailed sensor performance monitored in-flight by on-board calibrators.

CALIBRATION PHILOSOPHY

In-flight

On-board calibrators used to radiometrically calibrate MODIS:
- a) against the sun
- b) with reference to the preflight calibrations

On-board calibrators used to monitor: registration, MTF, and spectral response.

Many vicarious calibration results incorporated, including those using:
a) earth- and moon-surface sites for reflectance- and radiance-based calibration, and
b) for cross calibration with other EOS sensors.

CALIBRATION FEATURES UNIQUE TO MODIS

The EOS program is the first in which ultra-stable radiometers will be used to compare calibration sources to those in several national standards laboratories.

The spectral responses of the solar-reflective bands will be checked in flight.

Band-to-band registration will be checked and corrected along scan in flight.

MODIS is the first imaging sensor for which the stability of the solar diffuser will be monitored in flight using a ratioing radiometer.

The EOS program is the first in which the moon will be used to provide an absolute calibration in the solar reflective range.

CALIBRATION REQUIREMENTS

The following table lists the top-level calibration requirements and SBRC's predicted values. Several of these requirements are more demanding than for any earlier sensor of the MODIS type. The Calibration Plan describes how this challenge shall be met.

TABLE 1.1 TOP-LEVEL CALIBRATION REQUIREMENTS AND PREDICTED VALUES

Parameter	MODIS Requirement	Predicted Preflight	Predicted On-Orbit
Radiometric Calibration			
Below 1.0 µm	5%	4%	3%**
1.1 to 3.0 µm	5%	4%	3%**
Above 3 µm***	1%	1%	1%
Reflectance	2%	4%	2%
Spectral Calibration			
Center Wavelength	0.5 nm preflight, 1.0 nm on-orbit	0.5 nm	1.0 nm*
Spectral Band-to-Band Stability	0.5% FS 1.0% HS	0.5% FS 1.0% HS	0.5% FS
Geometric Calibration			
Band-to-Band Registration	0.2 IFOV	0.1 IFOV	0.15 IFOV
Diffuser BRDF			
<2.0 µm	0.5%		
2.0 to 2.5 µm	1.0%		

FS = Full Scale HS = Half Scale

* Dependent on good correlation with full aperture ground measurement and SRCA sub -aperture measurements

** Multiple calibration methodologies are required

*** Band 20 3/4%, bands 31 and 32 1/2% requirement

OBJECTIVES

There are four objectives for preflight cross calibration:

1. To minimize the differences, preflight between the calibrations of sensors that have similar spectral bandpasses.

For example ASTER, MISR and MODIS have some spectral bandpasses that are similar. In these bands they will each be measuring at-satellite spectral radiances. In some cases they will be imaging the same ground scene, under identical atmospheric, illumination and viewing conditions. Preflight cross calibration will minimize the likely errors introduced by the use of different calibration procedures and standards used by different instrument vendors in different countries.

OBJECTIVES (CONTINUED)

2. To minimize, through the use of ultra-stable radiometers, the differences between instruments being calibrated at different times, for example the MODIS on the first AM platform with the MODISs on later AM and PM platforms.

3. To ensure that the calibration of the instruments to be used to calibrate the moon are in agreement with EOS sensor preflight calibrations.

4. To cross calibrate the field instruments that will be used to validate the high-level-data products. It is particularly important to use the same ultra-stable radiometers that are used for preflight cross calibration purposes.

METHODOLOGY

Use of linear, ultra-stable radiometers, or spectrometers, to measure the integrating sphere and other solar-reflective sources, and blackbodies used to calibrate the EOS sensors.

The various transfer radiometers used for cross calibration purposes must be of different design in order to check for systematic errors introduced by the radiometers themselves.

The use of ultra-stable radiometers is considered more cost effective than attempting cross calibrations with a single artificial "universal" source.

ERROR BUDGET

Note: The following errors apply to the calibration sources used, not to the sensor calibrations themselves.

The error budget for a transfer radiometer is measured by its optical and temporal stability, (except in its use as an absolute radiometer, not addressed here).

Temporal stability is in terms of repeatability with time under varying conditions, such as change in temperature.

Optical stability is in terms of insensitivity to stray light, polarization, out-of-band radiance, non-linearity, etc.

Presently, one such instrument under test shows a standard deviation at a given radiance level of less than 0.26% of the average reading and most are less than 0.1% of the average. An instability of less than 0.5% is adequate for cross calibration purposes.

VERIFICATION

The verification of a cross calibration performed by a single transfer radiometer will be determined by:

1. Determining the stability of the radiometer.
2. Comparing results with those of other transfer radiometers.
3. Critically reviewing the error budget for the radiometer.
4. Carefully reviewing the measurements made to characterize its response.

PERSONNEL

One or two calibration scientists from: GSFC, NIST, NRLM, and UofA, and possibly other laboratories, will participate in the cross-calibration activities.

SCHEDULE

Cross-calibration round robins are scheduled to start in the summer of 1994. Past experience has indicated the need for detailed preliminary cross-calibration activities.

The plan for the actual cross-calibration campaign is to measure the output of the spheres and blackbodies at the levels that will be used for the calibrations of the sensors. The cross calibrations should take place as soon before and after the sensor calibration as possible.

The scheduling of these activities is the responsibility of the EOS Calibration Scientist.

CALIBRATION SITES

The sites to be visited for cross-calibration purposes are:

1. Fujitsu, MELCO, and NEC in Japan for ASTER
2. JPL for MISR
3. SBRC for MODIS
4. U of Toronto for MOPITT
5. possibly TRW for CERES
6. possibly Loral for AIRS

In addition there is the possibility of ATSR/Oxford, SPOT/Toulouse, and for ESA calibrations at Noordwijk.

RISK ASSESSMENT

Transfer radiometers are in the early phase of design, construction and evaluation. The work for the thermal infrared radiometers is expensive, mainly because they have to work in thermal vacuum conditions. With the March 1994 budget cut, work was stopped on the UofA thermal-infrared cross-calibration radiometer for use in thermal vacuum.

Scheduling may be a problem. Difficulties in obtaining access to facilities, particularly thermal vacuum chambers, and to the Japanese laboratory facilities for ASTER, are also of much concern.

OBJECTIVES

The primary objective is radiometrically to calibrate the total system, including the solar diffuser/solar-diffuser-stability monitor, with the same source and under the same geometrical conditions as used for the in-flight solar calibration.

Preflight, there is no plan, in the laboratory, to simulate the in-flight calibration with artificial sources. The calibration of the diffuser and the monitor have to be determined by separate characterizations, e.g., of the BRDF of the diffuser.

A secondary objective is to calibrate only the solar-diffuser-stability monitor outside. This has the disadvantage that the narrow spectral bands of MODIS are not calibrated against the sun.

Note that this method can only be used for the solar-reflective range.

OBJECTIVE -- ADVANTAGES

Solar-Radiation-Based Calibration (SRBC) provides an important link between integrating-sphere-source based calibration (with reference to national standards laboratories) and in-flight calibration using the solar diffuser. The reason is that the **same stable source is used in both cases and for all the reflected-radiance measurements of MODIS.**

SRBC also has the advantage, because it uses the sun, of including the effect of solar Fraunhofer absorption lines that must be accounted for in accurately calibrating sensors with 10-nm passbands.

It accounts for stray irradiance on the diffuser.

A second diffuser and transfer radiometer, could verify Labs and Neckel.

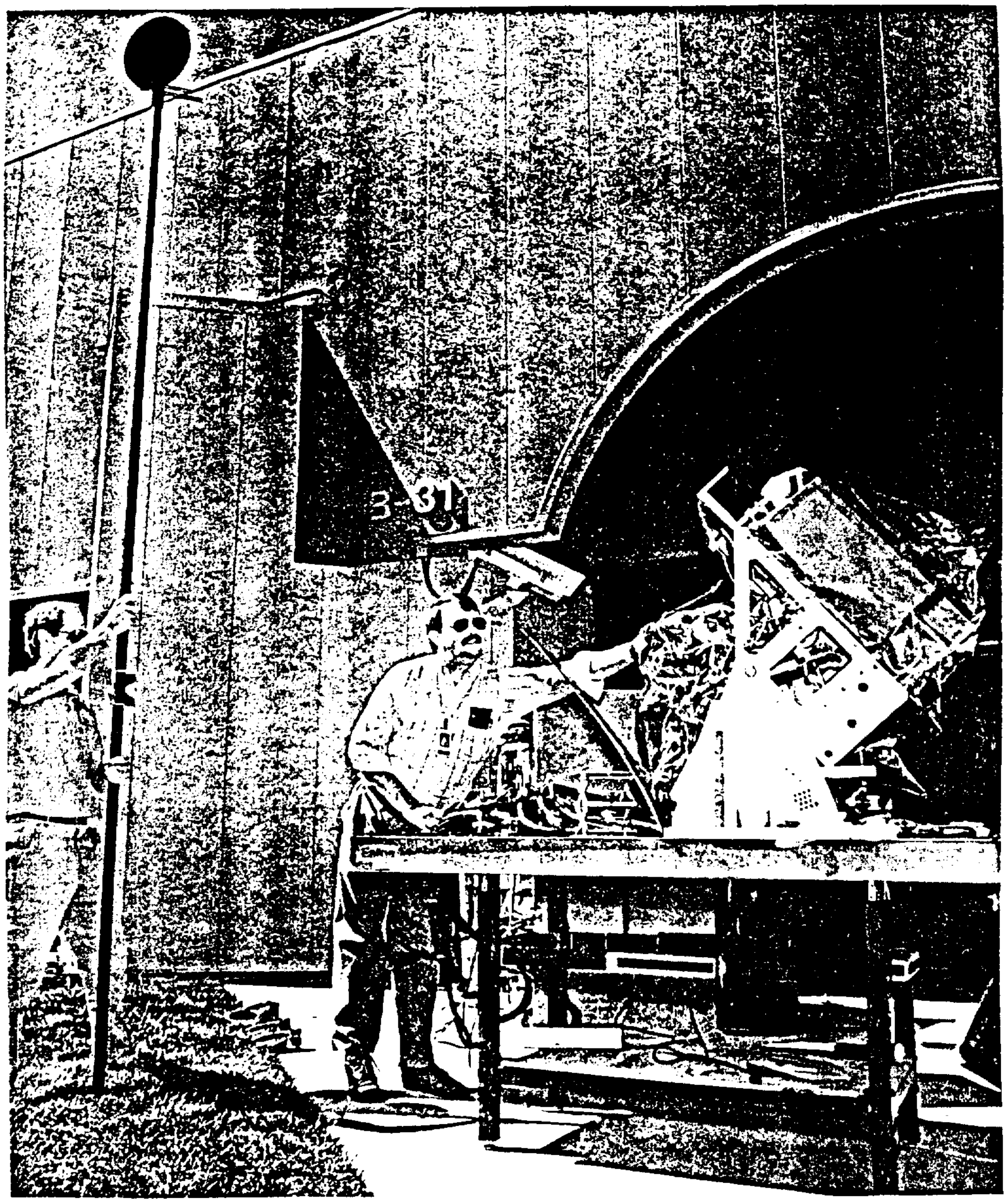
A complete SRBC takes less than one hour to perform.

METHODOLOGY

In brief the SRBC procedure involves:

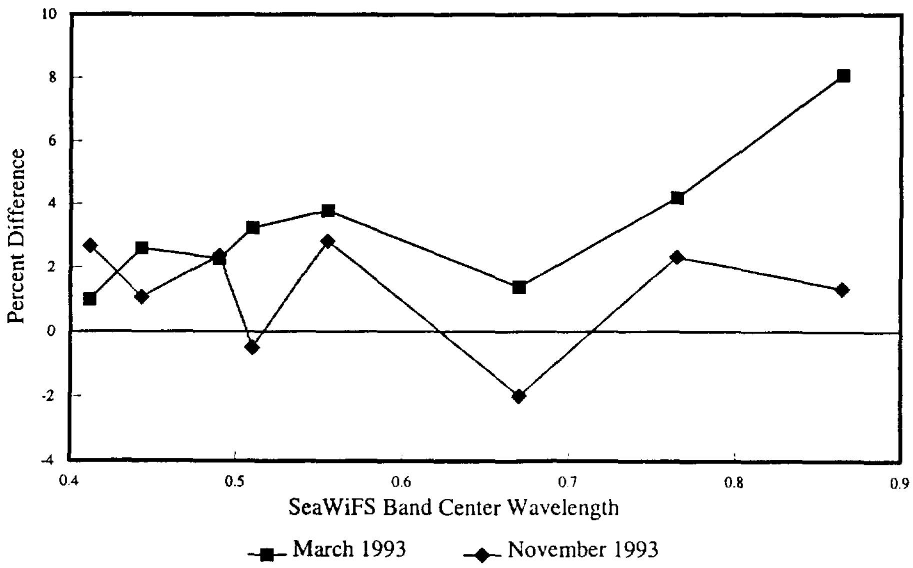
1. Illuminating the solar-diffuser panel with sunlight at the same angle as during on-orbit calibration.
2. Recording the digital counts (DCs) from all bands.
3. Occulting the direct solar beam so that only scattered sky light illuminates the panel.
4. Recording the DCs from all bands.
5. Subtracting (4) from (2) to give the DCs due only to the atmospherically attenuated solar beam.
6. Measuring the atmospheric attenuation with a solar radiometer.
7. Calculating the direct solar irradiance at the panel in each of the spectral bands from a knowledge of the center wavelength and band profiles and the solar exo-atmospheric spectral irradiance data of Labs and Neckel as published by Iqbal.
8. Combining (5) and (7) to give a point on the calibration curve of each spectral band.

PREFLIGHT SOLAR-RADIATION-BASED CALIBRATION



The solar-radiation-based calibration of SeaWiFS

COMPARISON WITH INTEGRATING-SPHERE-SOURCE RESULTS



ERROR BUDGET

The uncertainty of the method depends on several conditions:

1. Wavelength.
2. Solar zenith angle and elevation, i.e., air mass.
3. Atmospheric conditions, i.e., aerosol loading, thin cirrus.
4. The accuracy of the spectral transmittances derived from solar radiometry.
5. The accuracy with which the angle of incidence to the solar diffuser panel is known.
6. The accuracy of the Iqbal data for solar exo-atmospheric spectral irradiance. However, this is only of concern when reference to SI units in an absolute sense is needed.
7. The stability of the spectral response with time.

ERROR BUDGET

The largest source of uncertainty is in the sun-to-diffuser, atmospheric-path-spectral transmittance. The main source of error here is in the aerosol optical depth determination. This amounts to 3% of the output DCs which corresponds to a transmittance uncertainty of ±2.7% to ±1.1% corresponding to wavelengths of 400 nm and 900 nm respectively, for a solar zenith angle of 60°. These results are based on the use of an atmospheric model that assumed a 23-km visibility US standard atmosphere. For a solar zenith angle of 39°this uncertainty would be reduced by 1.65×.

Other errors arise in correcting for the occulting disc (0.8%) and in the uncertainty of measuring the angle of incidence (0.4%).

The total uncertainty is ± 2.8% to ±1.4% at a solar zenith angle of 60° to ±1.9% to 1.1% for a zenith angle of 39°.

VERIFICATION

The method will be verified during the initial in-flight calibration of SeaWiFS using the solar diffuser. The assumptions will have to be made that neither the solar diffuser nor the SeaWiFS instrument will have changed in their calibration since the preflight SRBC was conducted.

There are additional calibration checks, using the moon and a second diffuser panel, that should indicate if these assumptions are correct. If the solar calibration in flight agrees closely (say within 3%) to the preflight SRBC then the method will be considered verified. A second indirect and less reliable verification is through a comparison with the preflight spherical-integrating-sphere-source calibration.

PERSONNEL

Two calibration scientists from the Remote Sensing Group at the University of Arizona shall provide assistance to SBRC, particularly with the solar radiometer measurements and their conversion to spectral transmittances.

SCHEDULE

It is anticipated that the SRBC of MODIS shall be conducted following completion of the standard laboratory calibrations. It is desirable to have these calibrations and the cross calibrations conducted at about the same time (within a week or two of each other) to minimize the possibility of changes to the MODIS calibration between the preflight calibrations.

Some flexibility must be built into the schedule to allow for unfavorable atmospheric conditions.

CALIBRATION SITES

The calibrations shall be conducted at Santa Barbara Research Center.

There is the possibility of a solar-radiation-based calibration being conducted after MODIS has left SBRC.

RISK ASSESSMENT

At present there is a high probability that the complete sensor and solar diffuser/diffuser-stability-monitor calibration will **not** be conducted. The reason is that MODIS would either have to be operated outdoors or a heliostat would have to be located in a hole in the roof of the laboratory. The former introduces the risk of contamination, although this did not seem to be a problem with SeaWiFS which only had to be opened and exposed to the air for about 15 minutes. The location of a heliostat in the roof involves additional cost. There are enough present and potential future programs at SBRC that would benefit from this type of calibration that a cost-sharing approach appears attractive.

The fall-back solution is simply to calibrate the solar diffuser and its stability monitor outside. This is better than nothing, but does not calibrate the narrow MODIS bands with respect to the sun -- a major omission and calibration risk in itself.

OBJECTIVE

The objective is radiometrically to calibrate MODIS in flight using ground- and aircraft-based measurements to characterize the earth-atmosphere system. The results of these measurements are used in a radiative transfer code to predict the top-of-the-atmosphere radiances at the time of sensor overpass.

METHODOLOGY

Solar Reflective

Characterize surface reflectance and atmospheric scattering and absorption properties at time of overpass.

Thermal Infrared

Characterize surface emissivity and temperature and atmospheric temperature and moisture profiles at time of overpass.

Radiative Transfer Code

In both cases a radiative transfer code is used to infer the top-of-the-atmosphere radiance.

METHODOLOGY (CONTINUED)

HSR-to-LSR Calibration Transfer

For MODIS, in addition to using characterized, large, uniform targets (3 by 3 km in size), well-calibrated, high-spatial-resolution sensors may also be used to transfer calibration to MODIS.

Radiance-based

Makes use of a well-calibrated spectroradiometer in a low altitude aircraft (3-km MSL) to make spectral radiance measurements over the test site at the time of overpass.

ERROR BUDGET

Errors in reflectance-based approach occur primarily in the characterization of the aerosol scattering properties such as index of refraction and size distribution (2.0% and 3.0% respectively).

Total error in the reflectance-based approach is currently 4.9%, and 3.5% for the improved reflectance-based approach.

Errors in HSR-to-LSR calibration transfer are due to registration problems and spectral mismatch of the two sensors (~0.5% and ~1.0%).

The major error in the radiance-based approach stems from the absolute calibration uncertainty of the aircraft sensor (~2.5%). Uncertainties due to pointing, data logger accuracy, and other factors give rise to a total uncertainty of ~2.8%.

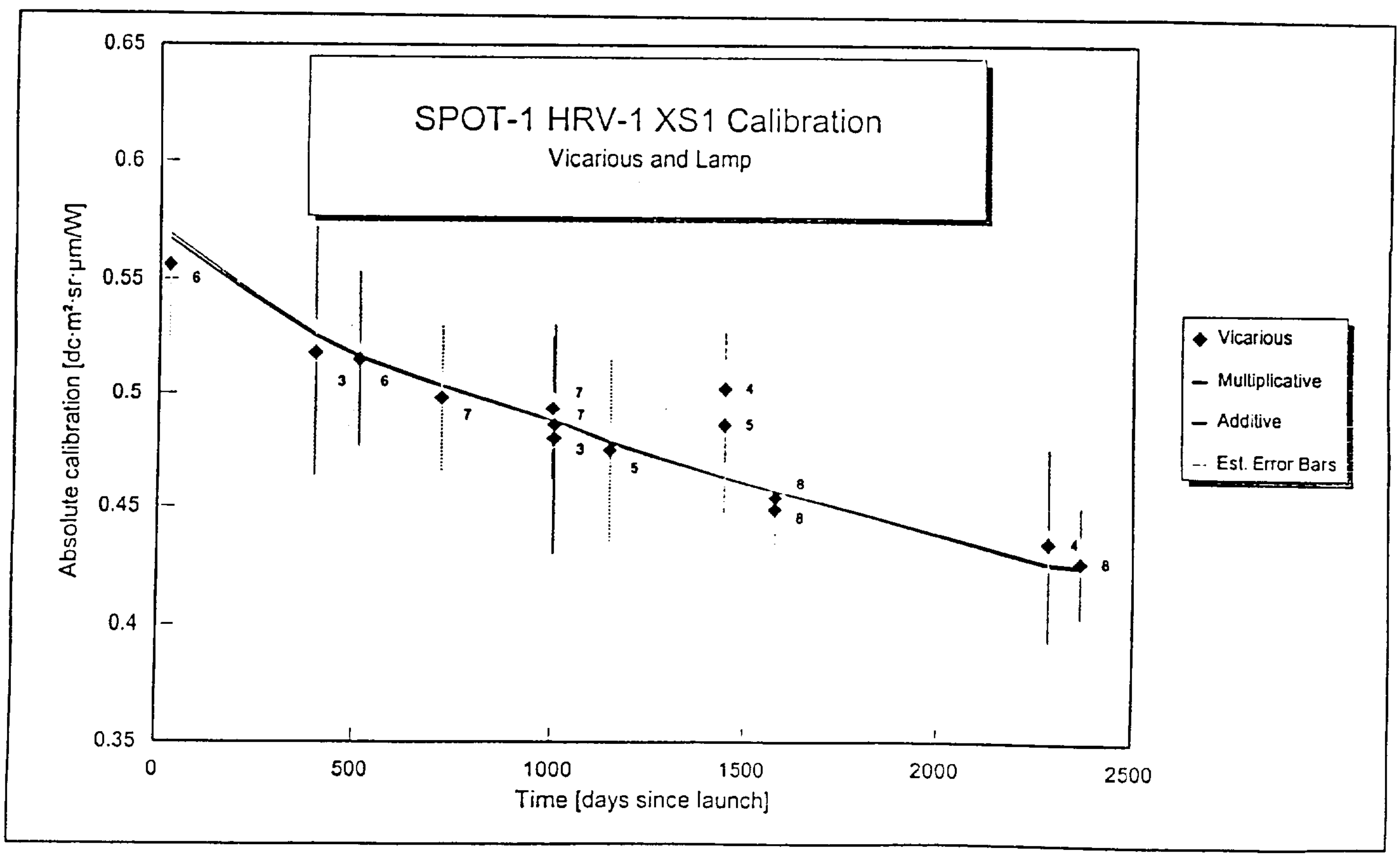
TABLE 7.1 Reflectance-based method error sources, with reference to solar xoatmospheric irradiance. The values are quoted as one-sigma percentages.

Source	Error	Total Error
Choice of aerosol complex index		2.0
Choice of aerosol size distribution		3.0
Type		
Size limits		0.2*
Junge parameter		0.5*
Optical depth measurement	5.4	1.1
Extinction optical depth	5.0	
Partition into Mie and Rayleigh	2.0	
Absorption computations		1.3
O_3 amount error	20.0	
Vertical distribution	1.0	1.0
Inherent code accuracy	1.0	1.0
Non-polarization vs. polarization code	0.1	0.1
Non-lambertian ground characteristic	1.2	1.2
Ground reflectance measurement		2.1
Reference panel calibration (BRF)	2.0	
Diffuse field correction	0.5	
Measurement	0.5	
Uncertainty in the value of $\mu_s = \cos(\theta_s)$	0.2	0.2
Total Error (root sum of squares)		4.9

* Included in the total error for choice of aerosol size distribution.

TABLE 7.3 Radiance-based method error sources.
The values are quoted as one-sigma percentages.

Source	Error	Total Error
Radiometer calibration		2.5
Panel calibration	2.0	
Lamp calibration	1.3	
Scale uncertainty	1.2	
Transfer uncertainty	0.5	
Lamp positioning	0.3	
Lamp current stability	0.5	
Voltage measurement error	0.5	
Measurement accuracy		1.3
Data logger accuracy	0.5	
Radiometer stability	0.5	
Pointing angle errors (± 10°)	1.1	
Correction for altitude difference		< 0.1
RTC uncertainty	5.0	
Total Error (root sum of squares)		2.8



VERIFICATION

Will be achieved through comparisons of values from several independent precise methods.

Verification of the reflectance-based results will be achieved through comparisons with the measured aircraft radiances from the radiance-based approach.

Verification of the radiance-based method will be achieved by comparing results from several different altitudes. The lowest altitude data will be compared with ground-based reflectance measurements by cross-calibrating to a reference diffuser panel on the ground.

PERSONNEL

Calibrations will be performed by members of the Remote Sensing Group of the Optical Sciences Center at the University of Arizona, who have over 30-man-years experience in this type of calibration.

SCHEDULE

The Remote Sensing Group is currently refining its measurement and processing techniques.

Techniques will be continually refined and evaluated prior to the launch of MODIS by using sensors already in orbit.

Calibration campaigns are expected to occur four-to-six times per year, once the sensor is operational. During the three-month activation and evaluation phase, four calibrations will be attempted.

CALIBRATION SITES

The Remote Sensing Group currently uses three sites: Rogers Dry Lake, White Sands Missile Range and Maricopa Agricultural Center.

Plans call for the RSG to use Lake Tahoe for the calibration of SeaWiFS. Its use will be evaluated for MODIS.

The RSG is currently investigating alternate sites with the following characteristics:

High, uniform reflectance and/or emissivity.
Clear dry atmosphere with low aerosol loading.
Readily accessible to the RSG, but not to the general public.

RISK ASSESSMENT

Low
~~Medium~~ Risk:

Proven methodology for high-spatial-resolution sensors.

Search for 3 × 3-km uniform sites underway.

HSR-to-LSR calibration transfer techniques are under investigation.

Work currently being funded and implemented.

OBJECTIVE

The objective of in-flight cross-calibration is to provide a comparison between the in-flight calibrations of the EOS imaging sensors that cover part or all of the same spectral region.

By providing such a comparison, the extent to which calibration differences between well characterized sensors producing the same data products at different scales will be known. Clearly, a knowledge of such differences is key to understanding any differences between level-1 and also higher level data products.

METHODOLOGY

In-flight cross-calibration between sensors can be conducted in several different situations when the sensors have:

1. The same IFOVs and spectral bands, and image the same scene simultaneously; for example, the two HRV cameras constituting a SPOT payload, and two nominally identical sensors, one in a transitional orbit.

2. Similar spectral bands that cover part or all of the same spectral range and still image the same scene simultaneously but with different IFOVs; for example, ASTER, MISR, and MODIS.

3. Similar spectral bands and IFOVs but do not image the same scene simultaneously; for example, ASTER/ATSR/Landsat TM/SPOT; MISR-AM or MODIS-AM/MODIS-PM; MISR/ or MODIS/AVHRR/HIRS-/TOVS/GOES/SeaWiFS.

METHODOLOGY (CONTINUED)

The methodology in all the above cases involves comparing spatially and spectrally uniform sites with two or more sensors. Provided the sensors are on the same platform, the comparisons can be conducted accurately with a correction for the spectral mismatch between the sensors. The spectral reflectance of the site has to be characterized in order for the mismatch to be corrected.

In the case of different sensors on different platforms, there are additional concerns. Again a spectral correction has to be made and, in addition, corrections for surface BRDF differences and atmospheric path differences for illumination and viewing have to be taken into account.

ERROR BUDGET

In case 1, the comparison should have a relative uncertainty of less than ±1%, one sigma. In case 2, the relative uncertainty has been estimated to be less than ±2%, one sigma. For case 3, the relative uncertainty has been shown to be in the range ±7% to ±10%, one sigma.

In cases 2 and 3, the errors are a function of spectral mismatch, and scene spectral and spatial uniformity. Work is in progress to identify the best scenes for the purpose.

VERIFICATION

The cross-calibration results are self verifiable. If agreement is found between two sensors but their results disagree with those from a third sensor, this will signal that a change has possibly taken place in the calibration of the third. Other methods for tracking calibration changes in the third sensor will then have to be checked to find if they reveal the same change.

The uncertainty of the method will be determined by statistically analyzing the results of several hundred cross comparisons. Because of different degrees of spectral band mismatching, such analyses will have to be conducted for each pair of bands that are cross calibrated.

PERSONNEL

These cross calibrations will be conducted by MODIS Science Team members from the Universities of Arizona and Wisconsin for land and water sites, and by the USGS/NAU team and MCST in conjunction with lunar calibrations, and probably by other members of the ASTER and MISR Science Teams.

Calibration scientists related to ATSR and SPOT have shown considerable interest in this work and it is likely that these and additional sensor-calibration scientists will also be involved.

SCHEDULE

Results from cross calibrations will probably be available at monthly intervals during the operational life of the sensors. Data will be collected more frequently during the activation and evaluation phase of AM and PM sensors.

The main scheduling problem will be with ASTER which acquires 60 × 60-km scenes. ASTER's mission planning will include acquisitions over selected sites for cross calibration purposes.

CALIBRATION SITES

The moon will be one site. Ground sites will be selected preflight from an examination of other satellite imagery. These sites will be chosen on the basis of their spectral and spatial uniformity. In most cases *in situ* spectral reflectance measurements will have to be made to provide inputs for the correction of spectral mismatch effects.

RISK ASSESSMENT

The greatest risk is with the lunar calibration. The uncertainty is in whether nadir views of the moon will be possible in order for ASTER and MISR to image the moon. Several possible spacecraft maneuvers are presently being studied by MMC.

The selection of potential ground sites is underway. Between 50 and 100 should be chosen by launch. It is expected that about half of these will be spectrally characterized by sensors such as ASAS, AVIRIS, ATSR, HYDICE, MAS, and other sensors in the next three years.